DEVELOPMENT OF A FUEL AIR PREMIXER FOR AERO-DERIVATIVE DRY LOW EMISSIONS COMBUSTORS.

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ABSTRACT

An experimental program was conducted to develop premixer concepts for use in GE's aero-derivative Marine and Industrial gas turbine engines such as the LM 1600, 2500 and 6000. These engines operate typically at pressure ratios up to 30:1. Extensive tests in 1 and 2 cup test combustors were carried out to evaluate the Double Annular Counter-Rotating Swirler (DACRS) premixers at test conditions representative of the above mentioned engines. These tests also help establish combustor design parameters. Single digit NOx emissions were measured at engine operating conditions with the DACRS II and III premixers. Premixer interactions and their effects on Lean Blow Out were also studied.

INTRODUCTION

The lean premixed combustion process offers several advantages over conventional wet NOx suppression systems. Expensive water treatment plants are not required and low emissions operation is possible for locations where water is at a premium. Lean premixed combustion has been chosen for the design of the low emissions combustion system for GE's LM series of aero-derivative marine and industrial gas turbine engines, including the LM6000, which is a derivative of the successful CF6-80C2 aircraft engine. The operating conditions of the LM 6000 engine, the highest pressure ratio engine in the LM family of engines, have been used to develop the lean premix combustion technology. The development of the Dry Low Emissions Combustion system of the LM6000 engine is described in greater detail by Leonard and Stegmaier (1993). Due to the advanced design of this engine, significantly higher pressure and inlet preheats have to be contended with in the design of the low emissions combustor using the lean premixed combustion process. Fuel/Air premixers that have been developed for Dry Low NOx combustors for heavy duty and other gas turbine engines are described in the literature (Sattelmayer et. al. 1990, Becker et.al. 1986, Smith et.al. 1986, Willis et.al. 1993). Such designs may not be suitable for advanced aero-derivative applications due to auto-ignition considerations and the limitations of size encountered in aero-derivative engines.

Auto-ignition times for fuels in the environment of an aero-derivative industrial gas turbine engine such as the LM6000 has been estimated to be in the range of 4 milliseconds (Lefebvre 1983). This necessitates that the mixing process take no more than 1 millisecond to complete at design point to afford a reasonable factor of safety. Although pure Methane has significantly larger auto-ignition times, it is conceivable that natural gas, with all likely species, could behave in a manner not too different from liquids when auto-ignition is concerned. Another limitation to the design of the premixer is flashback. Flashback typically takes place when the flame propagates upstream into the premixing duct. This phenomena has been observed in boundary layers where the forward velocity of air/fuel mixture is lower than turbulent flame propagation speed.

DLN COMBUSTOR DESIGN

The design of the LM6000 combustor followed the GE experience with parallel staged double and triple annular design methodology first developed in the low emissions programs in the seventies and the early eighties (Ekstedt 1987). The double/triple annular design of the combustor has several very significant advantages. The liner areas to be cooled are minimized. The package is small and thus will require minimal engine modifications to implement. The triple annular design was chosen due to the ease of staging permitted by the design. With the pilot dome in the center of the combustor, it is possible to generate 4 (pilot, pilot + inner, pilot + outer and pilot + inner + outer) staging modes of
The combustor/diffuser length had to be limited by the locations of the compressor exit guide vanes and the turbine nozzle. A multi-passage diffuser design allows the diffuser to be shortened. The maintainability constraint, that the fuel injection system be externally removable, requires that free space be maintained between the dome and the pre-diffuser, at least as much as required by the engagement of the fuel injection system (premixers). In order to maximize the residence time in the combustor for CO oxidation at part power conditions, the size of the premixer was apriori set at 0.05 m (2") for the mixing duct and 0.0175m (0.7") for the swirl vanes.

A cross-section of the LM6000 Dry Low Emissions combustor is shown in Figure 1. The size constraints become clear when the premixers must pass about 80% of the combustor air flow to keep the flame temperatures within limits where low NOx emissions can be maintained (Leonard and Stegmaier 1993), unlike conventional aero-engines where between 10 to 20% of the combustor air goes through the dome and the swirlers (Ekstedt 1987). The conventional radial inflow swirlers have been replaced by axial inflow premixers. In addition, to satisfy operability requirements the number of premixers has been increased to 75 (Leonard and Stegmaier 1993) in the triple dome arrangement. This reduces the air flow to each premixer to manageable levels. This arrangement, though very tight, has mechanical design advantages of having smaller liner surface area to cool. A general description of the combustion system can be found in Leonard and Stegmaier (1993). Since the low emissions combustor must fit inside the length restrictions of the existing turbomachinery, an additional length restriction is imposed on the combustion system design. The flame temperature in a low NOx emissions combustor is expected to be lower than that of conventional diffusion flame combustors. This together with wall quenching can result in increased CO emissions. The bulk residence time of the combustor must be maximized to minimize CO emissions. This requirement further constrains the premixer to be as short as possible, to maximize combustor length.

The work of Roffe and Venkataramani (1978) suggested that it was indeed feasible to get low NOx emissions at high pressures and temperatures representative of modern aero-derivative gas turbine engines. These researchers have used a perforated plate to conduct their experiments. Their work showed that the development of the premixer was challenging. Early groundwork on lean premixed combustion for gas turbines was laid in the works of Fenimore (1971), Leonard and Correa (1990 and Correa (1992). The development of heavy duty gas turbine combustion chambers using lean premixed combustion technology has been described by Davis (1992).

DACRS I DESIGN

The Double Annular Counter-Rotating Swirler (DACRS) premixer, shown in Figure 2, was conceived to satisfy the constraints of auto-ignition, flashback and size. The duct diameter is reduced at the exit (in comparison to its inlet) to continuously accelerate the air flow in an effort to reduce boundary layer thickness and limit growth of boundary layers to prevent flashback in the boundary layers. The area reduction is about 2:1. The exit velocity is set by design to be significantly greater than the turbulent flame speed in lean mixtures (Abdel-Gayed et.al. 1987). The mass averaged forward velocity is set to be greater than 84 m/sec (275 fps) for the prototype design. A conical centerbody along the centerline of the premixer can be utilized to supply liquid fuel to an atomizer at its tip and gas passages for diffusion burning at low power conditions.

Swirling flows in the duct give rise to free vortex like flows with a low static pressure region along the duct’s centerline. Such a situation typically leads to a recirculatory flow into the duct. This situation is clearly unacceptable. A counter-rotating inner swirler in the design helps increase the axial velocity along the centerbody and keeps the flow attached to the centerbody as well. The counter-rotating swirler also helps increase shear within the premixing duct. The
substantial increase in shear that this provides along the inner parts of the duct is expected to help mix the gaseous fuel with air. Air flow is split between the inner and the outer swirler in the 1:4 ratio. The premixers are designed for a 4% pressure drop across the dome.

In the design designated DACRS I, the fuel was injected into the air stream radially outwards from holes in the centerbody, just aft of the swirl vanes. The number of fuel jets was varied (4, 6, 8 and 12 holes) to alter jet penetration. A typical velocity profile measurement with a combination of +60-30 degrees (outer: inner swirler swirl angle) configuration is shown in Figure 3. Note the relative flat axial velocity profile. The measured swirl angle for this configuration is shown in Figure 4. This configuration was tested in a 1 cup test rig, at low pressures and a bistable mode of operation was seen. The NOx emissions were low (single digits) in one mode and extremely high (>100 ppm) in the other mode.

DACRS II DESIGN

The DACRS I configuration was modified by the addition of spokes in the location of the holes in the centerbody as shown in Figure 5. The spokes are expected to increase the penetration of the fuel and perform the task of 'Macro-mixing'. The new configuration is designated DACRS II. The first configuration tested had 8 spokes. The 0.125" diameter spokes have 3 holes to inject fuel into the air flow stream. The holes are located such that the fuel jet is perpendicular to the local air flow. The centerbody tip of the premixer was modified after low pressure tests to improve tip life. The downstream end of the centerbody was cooled by internal fuel impingement.

DACRS III DESIGN

The premixer designs described above have been modified further by the incorporation of fuel injection holes into the swirl-vanes of the outer swirler as shown in Figure 6. The fuel is injected through 3 holes in the trailing edge of each outer swirl vane and 1 hole in the outer wall of the mixing duct in between each swirl vane. The 10 outer and the 5 inner swirler vanes have aerodynamic shape to maximize flow coefficient. Fuel is fed to the hollow outer vanes through a manifold on the outside of the premixing duct. The centerbody of the
premixer is cooled by small amounts of purge air channelled through a small hole through the center. In addition it is shorter than the mixing duct which helps to keep it away from the flame. The basic design has been scaled to accommodate different air and fuel flows in the inner, the middle and the outer domes of the triple dome combustor.

1 CUP TEST APPARATUS

The single cup test combustor is shown in Figure 7. The premixer is attached to the upstream end of the 0.089m (3.5") nominal diameter cylindrical combustion chamber 0.15m (6") long. The length of the 1 cup test combustion chamber simulates the residence time of the LM6000 DLN combustor. The dome of the combustor is back-side cooled by convection using the premixer air. The cylindrical section is made of high temperature ceramic and is uncooled. Emissions measurements were made using an 'Aero-quench' probe designed per guidelines of Roffe and Venkataramani (1978). Care was exercised in the design of the gas sampling probe to minimize the backpressure at the gas sampling tip to ensure that a reasonable expansion pressure ratio (>5) was always maintained. Gas samples were carefully dried before injection into the NOx analyser. CO2, CO and UHC were also measured along with O2. The gas sampling system provides a backup method of calculating fuel air ratio. High pressure tests were performed using the blowdown facilities at General Applied Science Labs, Lake Ronkonkoma New York. Air flow for all tests is measured by a critical flow venturi before it passes through a pebble bed heater. A temperature feedback control is used to maintain constant air temperature throughout the 10 to 20 minute long tests. Air temperature and pressure is measured just upstream of the test combustion chamber. A pressure feedback control system is used to maintain combustion chamber pressure during each test. This pressure system permits the heat release to be modulated in the combustion chamber without changing its pressure. The choked flow inlet venturi keeps the air flow unchanged which maintains the dome velocity constant during the test.

2 CUP TEST APPARATUS

A two cup test apparatus has been designed to fit within the test rig shown in Figure 8. This test combustor has two premixers side by side and thus permits the evaluation of cup-cup interactions. The first design of this 2 cup test combustor has been implemented with ceramic uncooled sidewalls. The subsequent implementation has back-side cooled metal liner along with heat-shields on the dome which are similar those designed for the LM6000 combustor. The heatshields have been manufactured with a removable wall separating adjacent primary combustion zones. This additional feature permits the evaluation of interactions between adjacent primary combustion zones.

An elaborate checklist was used to ensure that all systems would function properly during the test. The air flow was set using a critical flow venturi and by regulating the pressure feeding the venturi. The fuel flow was measured using critical flow venturi flowmeters. Emissions were measured by aero-quench gas sampling probes. Two sets of probes were manufactured for the test. A radial traversing probe was used...
for most tests to generate emissions profiles across the exit plane of the combustion chamber. The axial probe was used for some tests to establish the axial emissions profile. Water was sprayed into the combustion chamber exit flows to cool the flow down to less than 533 K (500 F) for the backpressure valve.

DACRS II TEST RESULTS

The DACRS II premixer was tested at a variety of conditions representative of the LM series of gas turbine engines in the 1 cup test apparatus described above. The dome reference velocity (cold flow velocity) for most tests has been maintained close to 12 m/sec (40 fps). The radial profiles of emissions are measured with a single point radial traversing probe as shown in Figure 7. Representative emissions profile of NOx and CO are shown in Figure 9. The fact that the profiles are flat suggests that a representative sample could be taken along the centerline for gathering data. An axial emissions profile measured with an axial traversing sampling probe is shown in Figure 10. This measurement is restricted to the centerline of the 1 cup combustor due to rig limitations. Most of the heat release appears to have occurred in the first 0.05m (2") of the test combustor based on the combustion efficiency calculated using CO and CO2 emissions. Emissions data are shown in Figures 11 and 12. The NOx emissions, corrected to 15% oxygen dry, correlate over the test conditions to the flame temperature as seen in Figure 11. CO emissions have been measured close to the calculated equilibrium values. This is not surprising since the liner is not cooled. These measurements show that single digit NOx emissions goals are not out of reach of engine type hardware. The measurements of Leonard and Correa (1990) suggest that further improvements in design could lead to even lower NOx emissions.

The interaction of adjacent premixers has been studied in the 2 cup combustor apparatus described earlier. Figure 13 shows an emissions profile measured by a traversing gas sampling probe that travels across the 2 cup combustor with 1 premixer unfueled and the other premixer fully fueled. In the Figure 13a both premixers are fueled at the same equivalence ratio, the centerbody separating the primary combustion zones of the two premixers has been removed for this test. This configuration represents adjacent premixers within a dome of the triple dome combustor shown in Figure 1. In the Figure 13b, data shown correspond to the condition where an adjacent premixer within a dome has to be either switched on or has just been switched off. This configuration is transient in the combustor and occurs when the mode of combustor is being staged, i.e. another dome is being lit or switched off. The complete switching of the peak equivalence ratio measurement to the centerline of the non-burning cup suggests that tremendous mixing occurs within the 2 cup combustor. A strong secondary flow set up within the confines of the 2 cup liner transports the hot burning gases to the centerline of the non-burning premixer. Clearly there is significant mixing between the flows emanating from the two premixers. Figure 13c shows the dramatic impact of the centerbody separating the primary reaction zones of the two premixers. This configuration represents adjacent domes of the combustor. With the separation of the primary combustion zones, the strong secondary flow seen in Figure 13b is absent as seen by the significantly smaller equivalence ratio peak at the centerline of the non-burning premixer.
Figure 9. A representative radial profile of emissions from 1 cup test combustor. P3 = 30 atm, T3 = 755 K.

Figure 10. A representative axial profile of emissions from the 1 cup test combustor. P3 = 30 atm, T3 = 755 K.

Figure 11. NOx emissions from the DACRS II premixer at a variety of test conditions.

Figure 12. CO emissions from the DACRS II premixer at a variety of test conditions.

Figure 13. CO emissions from 2 cup test combustor with one premixer fueled at lower equivalence ratio and the other maintained at a constant equivalence ratio. P3 ~ 10 atm, T3 ~ 610 K.

Figure 14. Lean Blowout equivalence ratio in each of 2 premixers showing impact of adjacent premixers. P3 ~ 10 atm, T3 ~ 610 K.
Figure 13. Emissions profile measured across a 2 cup test combustor showing the impact on emissions of adjacent non burning premix the 2 primary combustion zones. P3= 18 atm, T3= 710 K.
A significant mixing layer appears to form between the adjacent premixer flows where partial quenching of the CO oxidation reactions appears. The extreme wall flows appear to be relatively unmixed since the CO emissions measured at the wall along the non-burning premixer is high, while the equivalence ratio is low and the CO emissions along the wall of the burning premixer is close to equilibrium while the equivalence ratio is almost equal to the premixer equivalence ratio. Figure 14 shows the impact on CO emissions of fueling adjacent cups, whose primary combustion zones are not separated by a centerbody, at different equivalence ratios. Mixing between adjacent premixers again appears to promote combustion in the under-fueled premixer. The impact of adjacent premixers without a separating wall on lean blowout is shown in Figure 15. When the fuel flow to both premixers is reduced simultaneously, lean blowout occurs as if the two premixer streams mix together before burning. When the fuel flow to one premixer is shut off, the other premixer blows out at a somewhat increased Lean blowout fuel flow. This suggests that small deviations in the equivalence ratios of adjacent premixers will be averaged out. This averaging is important since it helps increase the tolerance to variation in individual premixer air and fuel flows.

**DACRS III TEST RESULTS**

The DACRS III configuration has been tested in the 2 cup test combustor. The NOx emissions obtained with the DACRS III premixer design generally are similar to the DACRS II design and are shown for a variety of test conditions in Figure 16. As noted before this data is also correlated to the flame temperature in the two cup combustor. The data obtained by Leonard and Correa (1990) is significantly lower than the DACRS III data suggesting that further mixing improvements are possible. CO emissions data is shown in Figure 17. A typical radial traverse is shown in Figure 18. The quenching of CO oxidation reactions at the walls is clearly seen in the data. This type of quenching has been observed with the 2 cup test combustor with backside cooled sidewalls. The overall contribution of the increased CO emissions near the walls has been included in the emissions data shown in Figure 17. Interactions between adjacent premixers observed with the DACRS III premixer have almost been identical to that of the DACRS II premixers.

Dynamic pressures up to 5 psid pp were measured with the metal walled 2 cup test combustor. These dynamics did not adversely affect the operation of the tests though some hardware damage was encountered. The dynamic pressures could be reduced by increasing the dome pressure drop or changing the inlet air temperature. Little effort was expended in the conduct of these tests to suppress the dynamic pressures, however considerable effort was expended in recording the dynamic pressures.
The development plans for the LM6000 DLN combustor include 15 cup sector tests and full annular combustor tests before engine tests of the combustor. These tests will be conducted through the first quarter of 1994.

CONCLUSIONS

Lean premixed combustion is capable of reducing emissions from an aero-derivative gas turbine engine. Significant size and operating constraints (flashback, autignition etc) imposed by the lineage (aircraft engine) can be satisfied with compact premixer designs.

Both the DACRS II and DACRS III configuration are capable of operating with single digit NOx emissions at design points severe enough to represent the LM6000 engine. CO emissions in the 1 cup and the 2 cup test combustors of residence times representative of aero-derivative gas turbine engine combustors are close to equilibrium. The engine type hardware tested included the heat-shields on the dome and backside cooled liners. Though NOx goals of 25 ppm (corrected to 15% oxygen dry in exhaust) are within reach of the hardware tested, improvements can still be expected with further development. Adjacent premixer interactions are important to the design of the combustor. Small deviations due to tolerances can be accomodated by the design due to significant mixing of adjacent premixer flows. Separation of adjacent premixer primary zones decreases the mixing significantly, with a strong evidence of a large mixing region where CO burnout has been affected.

Significantly higher CO emissions occur close to the walls of the combustor apparently due to the quenching effect of backside cooled metal walls.

The DACRS II and DACRS III designs can be applied to all engines including the LM1600, the LM2500 and the LM6000, since single digit NOx emissions have been obtained at test conditions encompassing operating regions of these engines.

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